DRYING KINETICS OF TWO YAM (*Dioscorea alata)* VARIETIES

CINÉTICA DE SECADO EN DOS VARIEDADES DE NAME (*Dioscorea alata)*

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ABSTRACT: The aim of this research was the evaluation of the kinetics and the drying conditions, at laboratory scale, of two yam varieties (D. alata 9506-021 and 9506-027) from the germplasm bank of the University of Cordoba (Colombia). Two geometries (circular and square) were used for the study; the air temperature ranged from 40 to 70 °C and the air speed was $0.7\ m\ s^{-1}$. The experimental data were fitted appropriately to Fick, Page, and Logarithmic models. Mass transfer of the yam slices was described by using Fick's diffusion model, which was the best fitted model. Drying occurred mainly in the decline phase. Arrhenius described properly the dependency of the moisture diffusivity with temperature. Among the temperature range evaluated, moisture diffusivities varied from 1.70×10^{-9} to $6.84 \times 10^{-10}\ m^2/s$ and 1.33×10^{-9} to $6.30 \times 10^{-10}\ m^2/s$ for the D. alata 9506-21 and 9506-27, respectively. The drying activation energy for D. alata 9506-21 and 9506-27 varied from 23.19 to 25.72, and 16.03 to 17.82 kJ/mol, respectively.

KEYWORDS: effective diffusivity, Fick's model, Page's model, activation energy

RESUMEN: El objetivo de esta investigación fue la evaluación de la cinética y condiciones de secado, a escala de laboratorio, de dos variedades del ñame (D. alata 9506-021 y 9506-027) del banco de germoplasma de la Universidad de Córdoba (Colombia). Dos geometrías (circular y cuadrada) fueron utilizadas para el estudio; la temperatura del aire fue variada en un rango entre 40 a 70 °C y la velocidad de aire fue de $0.7\ m.s^{-1}$. Los datos experimentales se ajustaron apropiadamente a los modelos de Fick, Page y Logarítmico. La transferencia de masa del ñame fue descrita usando el modelo de difusión de Fick's, que fue el modelo que mejor se ajustó. El secado ocurrido principalmente en la fase de decreciente. La relación de Arrhenius describió satisfactoriamente la dependencia de la difusividad de la humedad con la temperatura. Entre el rango de temperatura evaluado, las difusividades de la humedad variaron de 1.70×10^{-9} a $6.84 \times 10^{-10}\ m^2/s$, y 1.33×10^{-9} a $6.30 \times 10^{-10}\ m^2/s$ para D. alata 9506-21 y 9506-27, respectivamente. La energía de activación para el secado de D. alata 9506-21 y 9506-27 varió de 23.19 a 25.72 y 16.03 a 17.82 kJ/mol, respectivamente.

PALABRAS CLAVE: difusividad efectivad, modelo de Fick, modelo de Page, energía de activación

1. INTRODUCTION

Yams (*Dioscorea spp.)* are an important source of carbohydrate for many people in Colombia, especially in the Caribbean Coast, where 97353 tons were, harvested in 10066 hectares during the year 2005 (DNP, 2006). Yams belong to the genus *Dioscorea* of the family *Dioscoreaceae*; which has about 600 species; among them *D. alata L.; D. cayenensis Lam, and D. rotundata Poir*, have the greatest economic importance (Montes et al., 2009). Yams are widespread and are one of the major staple foods in many tropical countries (Akanbi, Gureje & Adeyemi, 1996; Omonigbo & Ikenebomeh, 2000).

Yam is not considered to be a high-priority product, for this reason, an appropriate technological development has not been presented concerning the production and prosecution of this tuber. Besides its losses during the cultivation and gathering periods, there are also losses between 20 and 30 % during the post harvest because of the methods and infrastructure used are rudimentary. As a result, this leads the investigation into lack and modernization to industrial scale in order to achieve better conservation alternatives, use and decrease of losses (Guzmán & Buitrago, 2000)

Besides a moisture content of between 50 and 80 %, which makes it susceptible to deterioration, yam tubers comprise mainly of fiber, sugars, protein and starch, the last of which is found in the highest proportions (Opara, 1999). To overcome the high perishability of fresh tubers due to the high moisture contents, yams are processed into flour by peeling, slicing, blanching and sun-drying (Akissoe et al., 2001). Drying is a universal method for conditioning foods by the elimination of the water until a level that allows its balance with the ambient air, in such a way that preserves its physical and chemical characteristics (Ruiz & Montero, 2005). The removal of water in the solid foods arises initially, like a form of reduction of the water activity, inhibiting the microbial growth; therefore, it passes to also have significant importance in the reduction of energy costs, of transport, packing and storage of the foods that with high quantities of water (Cardoso, 2004).

Dried and milled yam is less perishable and can be consumed throughout the year, mainly to produce starch (Akingbala, Oguntimehin & Sobande, 1995; Akissoe et al., 2001). Thus the objectives of this research is to investigate the effects of yam variety and processing conditions on the drying characteristics, maximum content of starch and activation energy for drying of the yam their varieties *D. alata 9506-021 and 9506-027.*

2. MATERIAL AND METHODS

2.1 Drying pretreatments, procedure and conditions

Water yams (*Dioscorea alata*) were obtained from the germplasm bank from the PBA and University of Cordoba, Colombia. Average moisture content of *D. alata* was 87.7344 ± 0.2 % (wet basis). Yams were washed, manually peeled and cut into circular and square slices having the dimensions of 3.19 cm of radio and 5.6 x 5.6 cm, respectively, using very sharp stainless steel molds to carry out this procedure.

2.2 Drying procedure

The dryer system consisted of horizontal air flow through trays and was arranged as a closed circuit. For the air heating, three electric resistances were used (two of 1600 W and one of 800 W), which could be worked independently, controlled by a digital thermostat. A thermal-hygrometer (TESTO 635) was used in order to measure the dry bulb temperature as well as the drying air humidity. A digital anemometer (AIRFLOW Co. LCS 6000) was used to measure the drying air velocity (Fig. 1), designed and fabricated at the Department of foods Engineering, University of Cordoba, Monteria, Colombia. Drier was allowed to run for about an hour prior the loading of samples to allow the heated air to stabilize at the desired temperatures (40, 55, and 70 ºC) and at constant air velocity (0.7 m s^{-1}). Samples were loaded into the drier and removed at regular intervals until three consecutive weights were constant, indicating equilibrium condition.

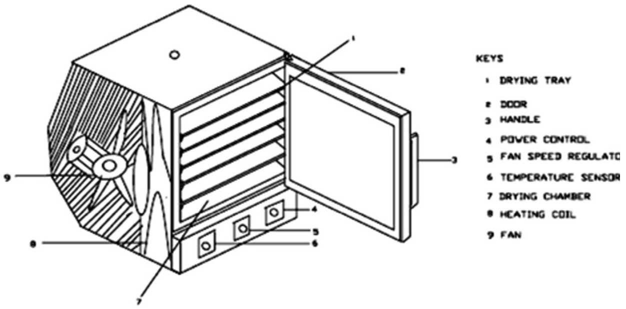

Figure 1. Isometric view of the fabricated air drier used for the drying of yam

Moisture contents at equilibrium were determined according to the method of AOAC (1997). Drying experiments were conducted in triplicate and average values reported.

The drying kinetics was studied by observing the drying curves for the considered air temperature and velocities.

2.3. Determination of drying characteristics

For model evaluation, a nonlinear regression procedure was used, for both models (Eqs. 5 and 6), using the statistical package Statistica 7.0 (StatSoft, Inc 2004). The modelling was characterized by the average relative error E (Eq. 1) calculation and the determination coefficient, R^2.

$$E(\%) = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{V_E - V_P}{V_E}\right|100 \quad (1)$$

where N is the number of experimental data, V_E is the experimental value and V_P is the calculated value.

It is generally assumed that the mechanism of moisture migration during thin layer drying of food materials is characterized by diffusion as described by Fick's second law of diffusion (Babalis & Belessiotis, 2004; Doymaz & Shovel, 2002; Luikov, 1966; Maskan, 2001; Saravacos, 1995; Senadeera et al., 2003).

An infinite slab of thickness 2L having the uniform initial water amount, undergoing drying under constant conditions can be described by Fick's unidirectional diffusion equation (Crank, 1975):

$$\frac{\partial WA(t)}{\partial t} = \frac{\partial}{\partial z}\left(D_{eff}\frac{\partial WA(t)}{\partial z}\right) \quad (2)$$

Using the following initial and boundary conditions:

uniform initial amount: $WA(z,0) = WA_0$

symmetry of concentration: $\left.\frac{\partial WA(t)}{\partial z}\right|_{z=0} = 0$,

equilibrium content at surface $WA(L,t) = WA_\infty$

and applying:

$$WA(t) = \frac{1}{L}\int_0^L WA(z,t)dz \quad (3)$$

Therefore, the solution as a series obtained for water transport in a cubic solid corresponds to the product of three perpendicular infinite slabs solutions (Crank, 1975; Treybal, 1981):

$$W = \frac{8}{\pi^2}\left(\sum_{i=0}^{\alpha}\frac{1}{(2i+1)^2}\exp\left(-(2i+1)^2\pi^2 D_{eff}\frac{t}{4L^2}\right)\right)^3 \quad (4)$$

where D_{eff} is the effective diffusivity of water (m^2/s), i is the number of series terms, L is the characteristic length, sample half-thickness (m), t is the drying time (s), W is the dimensionless amount of water defined by Eq. (5).

$$W = \frac{WA(t) - WA_\alpha}{WA_0 - WA_\alpha} \quad (5)$$

where WA_0 is the initial water amount (g), WA_∞ is the equilibrium water amount (g) and $WA(t)$ is the average water amount at instant t (g).

Eq. (4) can be used in terms of moisture content:

$$M = \frac{X(t) - X_\alpha}{X_0 - X_\alpha}$$

$$M = \frac{8}{\pi^2}\left(\sum_{i=0}^{\alpha}\frac{1}{(2i+1)^2}\exp\left(-(2i+1)^2\pi^2 D_{eff}\frac{t}{4L^2}\right)\right)^3 \quad (6)$$

where M is the dimensionless moisture ratio, X_0 is the initial moisture content (g water/100 g dry matter), X_∞ is the equilibrium moisture content (g water/100 g dry matter), and $X(t)$ is the average moisture content at instant t (g water/100 g dry matter).

One of the most useful empirical models is Page's equation (Page, 1949), which is an empirical modification of the simple exponential model. It is written in the form:

$$MR = \frac{X_{(t)} - X_\alpha}{X_0 - X_\alpha} = Exp\left(-kt^n\right) \quad (7)$$

where k is the drying constant, n is the Page's parameter and t is the process time (s).

The empirical logarithmic model is also used as a good approximation to explain the kinetics and drying conditions (Ertekin & Yaldiz, 2004); it is written in the form:

$$MR = a\left[Exp\left(-k_1 t\right)\right] + c \quad (8)$$

where k_1 is the drying constant, a and c are the models parameter and t is the process time (s).

Karatas (1997) and Senadeera et al. (2003) reported the correlation between the drying conditions and the values of the effective diffusivity using Arrhenius type equation:

$$D_f = D_0.Exp\left(-\frac{E_a}{RT}\right) \quad (9)$$

Where D_0 is diffusion coefficient; E_a is activation energy (kJ/mol); R is universal gas constant (8.314 J/mol K) and T is absolute air temperature (K).

2.4. Statistical analysis

Results were evaluated for analysis of variance (ANOVA) using Statistica 7.0 (StatSoft, Inc., 2004).

3. RESULTS AND DISCUSSION

3.1 Effect of temperature, geometry and variety on moisture ratio and drying rates of yam.

Figures 2 and 3 show the effect of temperature on moisture ratio of *D. alata* during air-drying, for varieties 9506-21 and 9506-27 with circular geometry. Moisture ratio decreased with increasing drying temperature. The similar tendency was exhibited by the square geometry for both varieties (Figs. 4 and 5). With the variance analysis to 95 % of dependability (Table 1), it is confirmed that the temperature affects in a notable from, the drying time, being corroborated this way the coherence that is reflected among the statistical analysis and in drying rate curve; while variables as geometry, variety and the existent interactions among the variety, geometry, and temperature are not influential in the behavior of the drying time.

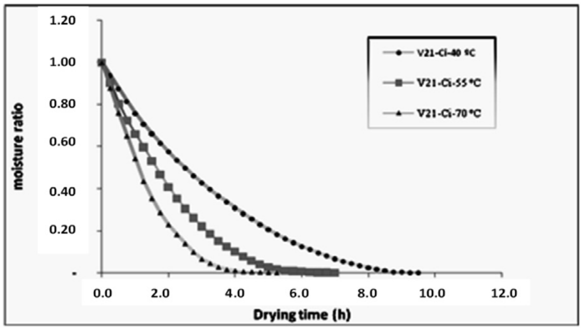

Figure 2. Effect of temperature on *D. alata* during air-drying, for variety 9506-21 circular geometry

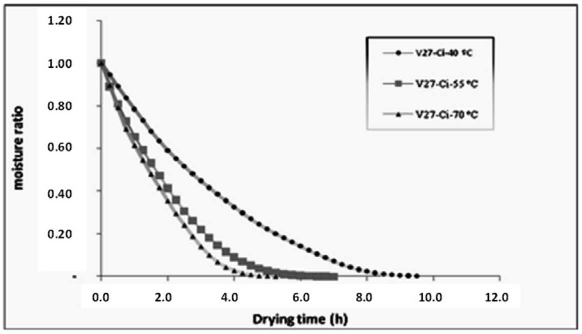

Figure 3. Effect of temperature on *D. alata* during air-drying, for variety 9506-27 circular geometry

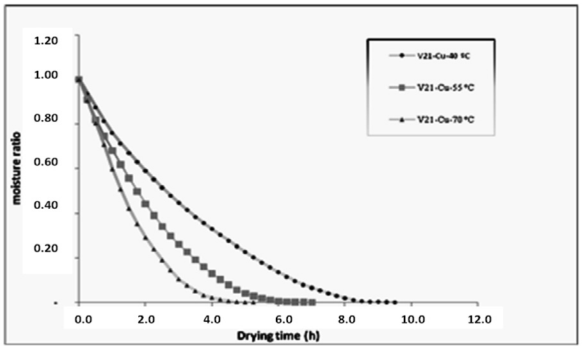

Figure 4. Effect of temperature on *D. alata* during air-drying, for variety 9506-21 square geometry

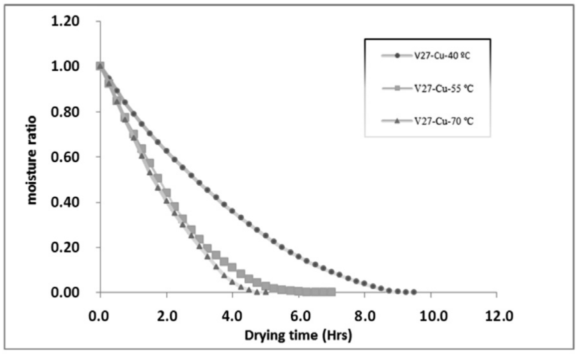

Figure 5. Effect of temperature on *D. alata* during air-drying, for variety 9506-27 square geometry

Table 1. Analysis of variance (ANOVA) for drying time

	D.F	SS	MS	F	p-value
Temperature	2	445850	222925	4458.5	0.000000
Geometry	1	0	0	0.0	1.000000
Variety	1	25	25	0.5	0.486310
Temperature*Geometry	2	0	0	0.0	1.000000
Temperature*Variety	2	50	25	0.5	0.612710
Geometry*Variety	1	25	25	0.5	0.486310
Temperature*Geometry*Variety	2	50	25	0.5	0.612710
Error	24	1200	50		
Total	35	447200			

* Level of significance of 5%

This behavior could be due to that the varieties used in the drying process belong to the same gender, they were cultivated under the same environmental conditions, floor type, nutritious and time of crop, presenting structure therefore interns similar; and as for the geometry the superficial area of each sample was same for all the treatments, prevailing this variable with regard to the form. Generally, in one hand, higher drying temperatures resulted in steeper curves and shorter drying times. The time required to reduce the moisture ratio to any given level was dependent on the drying temperature. According to Doymaz (2005), the effect of drying air temperature was most dramatic with moisture ratio, moisture ratio decreased rapidly with increased drying air temperature. These results were also obtained for Park, Vohnkova & Brod (2002); Maldonado & Pacheco (2003); Vega & Fito (2005); Simal, Dey & Rossell*,* (1997); Doymaz (2005); Mohapatra & Rao (2005); Vega & Lemus (2006) and Ocampo (2006), working with other species; vegetables and cereals. On the other hand, just the first three hours of drying from the total ten ones to obtain the constant humidity (Figures 2–5), free humidity decreased lineally with the time, drying occurred predominantly in the falling rate period. This showed that diffusion is the dominant physical mechanism governing moisture movements in the yam samples. Similar results were reported for greenbean (Rosello et al*.,* 1997), okra (Doymaz, 2004a; Gogus & Maskan, 1999), red chilli (Gupta, et al*.,* 2002), Carrot (Doymaz, 2004b; Prabhanjan, Ramaswamy & Raghavan*,* 1995) and eggplant (Ertekin & Yaldiz, 2004).

3.2 Modelling of drying kinetics curves

The experimental data of drying were adjusted to the mathematical models Fick's, Page's, and the Logarithmic (Tables 2, 3, and 4). According to the obtained adjustments and to the evaluation of each proposed pattern and using the coefficient of determination (R^2), the sum of square of the model (SCM) and the sum of square of the error (SCE), it was determined that the model that better describes the behavior of the data of *D. alata* during air-drying, for varieties 9506-21 and 9506-27 in geometries circular and square for the temperatures of 40, 55, and 70 ºC, it is the Logarithmic. In the Table 4 can observe as the parameter K_1 their value it increases with the increment of the temperature, coinciding this result with the obtained by Ertekin & Yaldiz (2004); Correa, da Silva & Almeida (2004); Babilis & Belessiotis (2004); Vega & Fito (2005); Vega & Lemus (2006), and Falade et al. (2006) for the eggplant drying, onion, fig, red pepper, Chilean papaya and yam (varieties *D. alata* and *D. rotundata*), respectively. In the same sense, the parameters a and b don't vary significantly for the geometries and the varieties, being these results confirmed with the variance analysis (ANOVA) for these constants at a level of dependability of 95 %.

Table 2. Page's equation parameters of *D. alata*, for two varieties (9506-21 and 9506-21) and two geometries (circular and square)

Variety	Temperature	Geometry	K	n	R^2	SCR	SCE
9506-21	40	Circular	0.235	1.214	0.990	21.977	0.104
		square	0.220	1.232	0.980	22.657	0.216
	55	Circular	0.395	1.256	0.993	14.603	0.055
		square	0.357	1.262	0.991	15.655	0.076
	70	Circular	0.623	1.293	0.990	10.752	0.064
		square	0.504	1.349	0.968	12.293	0.215
9506-27	40	Circular	0.211	1.256	0.994	23.164	0.066
		square	0.187	1.282	0.990	24.728	0.109
	55	Circular	0.394	1.263	0.990	14.552	0.078
		square	0.332	1.367	0.995	15.949	0.044
	70	Circular	0.460	1.309	0.992	12.949	0.050
		square	0.358	1.418	0.990	14.972	0.070

Table 3. Fick's equation parameters of *D. alata,* for two varieties (9506-21 and 9506-21) and two geometries (circular and square)

Variety	Temperature	Geometry	K	R2	SCR	SCE
9506-21	40	Circular	0.258	0.914	21.174	0.907
		square	0.249	0.902	21.816	1.057
	55	Circular	0.415	0.918	14.006	0.652
		square	0.382	0.911	15.013	0.719
	70	Circular	0.607	0.913	10.262	0.554
		square	0.526	0.878	11.676	0.831
9506-27	40	Circular	0.247	0.908	22.228	1.002
		square	0.229	0.897	23.717	1.120
	55	Circular	0.416	0.915	13.954	0.676
		square	0.392	0.899	15.131	0.862
	70	Circular	0.479	0.903	12.374	0.624
		square	0.418	0.874	14.178	0.864

Table 4. Logarithmic equation parameters of *D. alata*, for two varieties (9506-21 and 9506-21) and two geometries (circular and square)

Variety	Temperature	Geometry	a	K	C	R2	SCR	SCE
9506-21	40	Circular	1.144	0.239	-0.138	0.995	22.024	0.057
		square	1.175	0.216	-0.177	0.987	22.730	0.143
	55	Circular	1.118	0.413	-0.096	0.994	14.608	0.050
		square	1.143	0.361	-0.127	0.993	15.675	0.057
	70	Circular	1.111	0.645	-0.069	0.987	10.732	0.085
		square	1.156	0.524	-0.110	0.965	12.272	0.235
9506-27	40	Circular	1.180	0.222	-0.165	0.998	23.212	0.018
		square	1.233	0.189	-0.226	0.996	24.792	0.045
	55	Circular	1.119	0.411	-0.099	0.991	14.556	0.074
		square	1.168	0.382	-0.123	0.992	15.925	0.068
	70	Circular	1.184	0.427	-0.166	0.995	12.967	0.031
		square	1.309	0.330	-0.276	0.992	14.988	0.054

3.3 Diffusivity of yam slices

Diffusion method was used in the study of the transfer of mass of agricultural products (Vega & Fito, 2005). For the case of the *D. alata* the integrated equation of the second law of Fick was used (Eq. 6) for long times and plane geometry in a dimension. The effective diffusivity (D_f) for each temperature it could be to adjusting the experimental data for non lineal regression.

The effective diffusivity (D_f) presents a direct relation with to the temperature, and they are independent of the geometry and of the varieties (Table 5). In general, those calculated of the coefficients diffusive starting from the experimental data, they presented a good adjustment to Arrhenius equation (Table 6).

Table 5. Moisture diffusivity (m^2/s) of *D. alata*, for two varieties (9506-21 and 9506-21) and two geometries (circular and square)

Temperature °C	Variety 9506-21		Variety 9506-27	
	Circular	Square	Circular	Square
70	1.70E-09	1.51E-09	1.33E-09	1.15E-09
55	1.15E-09	1.06E-09	1.17E-09	1.04E-09
40	7.03E-09	6.48E-10	6.70E-10	6.30E-10

Table 6. Diffusion coefficient (D_0) and activation energy (Ea) mass diffusion, during air dying, of D. alata, for two varieties (9506-21 and 9506-21) and two geometries (circular and square)

	Variety 9506-21		Variety 9506-27	
Parameters	Circular	Square	Circular	Square
D_0 (m^2s^{-1})	1.40E-05	5.12E-06	7.10E-07	3.29E-07
Ea(kJmol^{-1}	25.72	23.19	17.82	16.03
R^2	0.93	0.877	0.874	0.78
SCR	1.41E-17	1.16E-17	1.06E-17	8.33E-18
SCE	1.21E-19	2.50E-19	1,11E-16	7.79E-20

3.4. Activation energy for drying of yam.

With the values of effective diffusivity to the different temperatures, the activation energy (kJ/mol) for drying was calculated, for the two geometry and the two varieties, for non lineal regression starting from the equation of Arrhenius, with high determination coefficients (R^2 = 0.870 - 0.930), indicating a good fit (Table 6). Activation energy for drying is the energy required to initiate mass diffusion from a wet food material during drying (Mittal, 1999). Activation energy for drying ranged from 23.19 to 25.72 and 16.03 to 17.82 kJ/mol for *D. alata* variety 9506-21 and variety 9506-27 respectively (Table 6), however, varieties and geometries showed no significant effect ($p < 0.05$) on activation energy for mass diffusion. Activation energy (Ea) obtained in our work is comparable with existing literatures for *D. alata*, 25.26 to 46.46 kJ/mol (Falades et al., 2006); carrot, 28.39 kJ/mol (Doymaz, 2004b), and potato, 20.0 kJ/mol (Bon et al., 1997). Values of the energy of activation lie within the general range of 12.7–110 kJ/mol for food materials (Zogzas, Maroulis & Marine-Kouris, 1996).

4. CONCLUSIONS

Increasing in air temperature caused a reduction in the drying time of the yams, but the variety and the geometry do not influence it.

Fick’s, Page’s, and logarithmic models showeds a good fit to the experimental data, nevertheless, this last is the one that better describe them, with a good coefficient of determination (below 0.96) and the sums of (deviation) squares errors were below 0.3. Fick’s, Page’s, and logarithmic equation parameters did not exhibit a clear trend with varieties and geometries, but the air temperature had some influence on drying constant.

The increase of air temperature and air velocity increased the effective water diffusivity values.

Activation energy to dry off is affected by the variety of the yam but not significantly ($p < 0.05$). Activation energy for the *D. alata* 9506-21 (23.19–25.72 kJ/mol) it was significantly higher than the *D. alata* 9506-27. (16.03–17.82 kJ/mol).

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